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Distinguishing anomaly-mediation from gauge-mediation with a Wino NLSP

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Abstract

A striking consequence of supersymmetry breaking communicated purely via the superconformal anomaly is that the gaugino masses are proportional to the gauge β-functions. This result, however, is not unique to anomaly-mediation. We present examples of "generalized" gauge-mediated models with messengers in standard model representations that give nearly identical predictions for the gaugino masses, but positive (mass)^2 for all sleptons. There are remarkable similarities between an anomaly-mediated model with a small additional universal mass added to all scalars and the gauge-mediated models with a long-lived Wino next-to-lightest supersymmetric particle (NLSP), leading to only a small set of observables that provide robust distinguishing criteria. These include ratios of the heaviest to lightest selectrons, smuons, and stops. The sign of the gluino soft mass an unambiguous distinction, but requires measuring a difficult class of one-loop radiative corrections to sparticle interactions. A high precision measurement of the Higgs-b-$\bar{b}$ coupling is probably the most promising interaction from which this sign might be extracted.

1 Introduction

Supersymmetry breaking communicated dominantly via the superconformal anomaly is a very interesting new approach to weak scale supersymmetry [1, 2]. In the absence of singlets, anomaly-mediation provides a one-loop contribution to the gaugino masses, a one-loop contribution to the scalar trilinear couplings, and a two-loop contribution to the scalar $(\text{mass})^2$ of the minimal supersymmetric standard model (MSSM). These contributions can be understood as arising from a super-Weyl invariant action once supersymmetry breaking is explicitly included in the superconformal compensator in supergravity, and are thus precisely proportional to the gravitino mass. If there are no direct couplings between the MSSM sector and the supersymmetry breaking sector, then anomaly-mediation provides the dominant contribution to all the MSSM fields. This is a natural expectation if the MSSM fields and the supersymmetry breaking sector fields are physically separated on different branes [1].

There are several advantages to the anomaly-mediation approach. The supersymmetric flavor problem is ameliorated, since the potentially dangerous contributions to off-diagonal squark $(\text{mass})^2$ are suppressed. The form of the expressions for the masses induced via the superconformal anomaly are exact to all orders [2, 3], and determined by infrared physics, namely the low energy β-functions. Finally, the ratio of gaugino masses to scalar masses is order one (i.e. *not* one-loop suppressed).

Gauge-mediation [4, 5] shares several features with anomaly-mediation, namely the supersymmetric flavor problem is also ameliorated, and masses are induced at one-loop for gauginos and $(\text{mass})^2$ are induced at two-loops for scalars. Furthermore, gauge-mediated gaugino masses are (at leading order) proportional to the gauge $(\text{coupling})^2$, identical to anomaly-mediation. The key phenomenological difference is that gauge-mediated soft masses depend on the content of the messenger sector, whereas anomaly-mediated soft masses depend on the low energy β-function coefficients. More generally, supersymmetry breaking masses are determined by ultraviolet physics in gauge-mediation, and by infrared physics in pure[1] anomaly-mediation. In general the phenomenology is expected to be quite different, but there is no a priori reason why these two fundamentally different origins of supersymmetry breaking masses could not be "accidentally" rather similar. We show that a simple choice of messenger matter using standard model (SM) representations gives the same numerical result for the size of gaugino masses at leading order. Other messenger sectors that give similar results are also briefly mentioned. At next-to-leading order there are two-loop contributions to gaugino masses that do not respect the leading-order equivalence. However, there is still a restricted range of gauge-mediated parameters that give gaugino masses that are nearly equivalent to the next-to-leading order predictions of anomaly-mediation.

The scalar spectrum of a gauge-mediated model is well defined once the messenger sector is fixed. This suggests that a gauge-mediated model could be falsified simply by measuring

[1] "Pure" meaning an anomaly-mediated MSSM without any additions or modifications, and thus without a solution to the negative slepton $(\text{mass})^2$ problem.

several slepton and squark masses in addition to the gaugino masses, and then determining if the spectrum is self-consistent. On closer inspection, however, the situation is not quite so trivial. The first and second generation squark masses are nearly identical to the pure anomaly-mediated result in "generalized messenger" gauge-mediated models. (Third generation squark masses are somewhat more distinct, but complicated by left-right mixing.) Furthermore, pure anomaly-mediation predicts slepton (mass)^2 that are negative, requiring one of several proposed remedies [1, 2, 6, 7, 8, 9, 10, 11]. Each "solution" to the negative slepton (mass)^2 problem must at least provide additional contributions to the slepton masses, and can have varying effects on the remainder of the mass mass spectrum. In this paper, we employ the simple phenomenological solution that merely adds a universal (mass)^2 term to all of the scalar masses, leaving the gaugino masses unchanged [7, 10]. A more drastic alternative that, for example, shifts the gaugino masses from their anomaly-mediated values would be trivially distinct from the gauge-mediated models discussed here, and thus need not be considered further.

There are at least two other general distinctions between gauge-mediation and anomaly-mediation: The Wino NLSP is not stable in gauge-mediation, and the sign of the gluino soft mass is opposite (negative) in anomaly-mediation. The extent to which these distinctions are phenomenologically useful criteria is also discussed.

Our main purpose in this paper is not to advocate that the gauge-mediated Wino NLSP models are more (or less) favored than an anomaly-mediated model with an appropriate negative slepton (mass)^2 solution. Instead, we are interested in determining the ways to experimentally verify (or falsify) these scenarios. Our starting point is that a gaugino mass spectrum that is approximately proportional to gauge β-functions is *not* sufficient to identify anomaly-mediation as the source of supersymmetry breaking. Instead, several other criteria must be used to separate the gauge-mediated models discussed here from anomaly-mediation. In this way we attempt to gain a more robust understanding of the signals of both anomaly-mediation and gauge-mediation.

2 Constructing a model

A wide class of "generalized" gauge-mediated models lead to the identification of the neutral Wino as the next-to-lightest sparticle (NLSP) [12]. Here we focus on perhaps the most interesting (and problematic) scenario, namely gaugino masses that are generated from a gauge-mediated scenario that are in the same proportions as expected from anomaly-mediation.

To begin, anomaly-mediation (AM) predicts the gaugino masses are

$$\begin{aligned} M_a^{\rm AM} &= \frac{\beta_a}{g_a} m_{3/2} \\ &\simeq B_a^{(1)} \frac{g_a^2}{16\pi^2} m_{3/2} \,, \end{aligned} \tag{1}$$

where $m_{3/2}$ is the gravitino mass, g_a is the gauge coupling,[2] and $B_a^{(1)} = (33/5, 1, -3)$ correspond

[2] g_1 is always taken to be in the GUT normalization, $g_1 = \sqrt{5/3}g'$.

to the one-loop β-function coefficients for $a = [\mathrm{U}(1)_Y,\ \mathrm{SU}(2)_L,\ \mathrm{SU}(3)_c]$. For the purposes of this section, only effects to leading order (i.e. to one-loop for gaugino masses) will be discussed. The anomaly-mediated expression can be contrasted with the expression for gaugino masses in gauge-mediation (GM)

$$M_a^{\mathrm{GM}} = \frac{g_a^2}{16\pi^2}\sum_i S_a(i) g(F_i/M_i^2)\frac{F_i}{M_i} \tag{2}$$

where the sum is over all messengers labeled by i, $S_a(i)$ is the Dynkin index for the a gauge group, and F_i and M_i are the F-terms and fermion masses of the messengers. The function $g(x)$ is

$$g(x) = \frac{1}{x^2}\left[(1+x)\log(1+x) + (1-x)\log(1-x)\right] \ , \tag{3}$$

and is equal to about $1, 1.05, 1.22, 1.39$ for $x = 0, 0.5, 0.9, 1$. In the approximation $F_i = F \ll M_i^2 = M^2$, and writing the summed Dynkin index as $n_a = \sum_i S_a(i)$, the expressions for the gaugino masses in the two classes of models are identical under the substitution $B_a^{(1)} \leftrightarrow n_a$.

2.1 Generalized messenger models

This suggests a strategy to construct a gauge-mediated model with gaugino masses proportional to the one-loop β-functions. Require

$$n_a = |B_a^{(1)}| \tag{4}$$

and $F/M = m_{3/2}$, then the gaugino masses are identical to anomaly-mediation up to the sign of the gluino soft mass.[3] The differing sign has a limited impact. It does affect the gaugino soft mass predictions at next-to-leading (two-loop) order, and we discuss this in more detail in Sec. 4. In principle measuring this sign would be an unambiguous way of distinguishing these models, but experimentally this is rather difficult, as we explain in Sec. 3.2. Suffice to say there is no easily measurable difference between a model with a positive gluino soft mass, such as gauge-mediation, and a model with a negative gluino soft mass, such as anomaly-mediation.

The ratio F/M that sets the overall scale of the gauge-mediated soft masses is an unknown parameter that need not be equivalent to $m_{3/2}$. At first glance, therefore, only the proportionality $(n_1 : n_2 : n_3) = (B_1^{(1)} : B_2^{(1)} : |B_3^{(1)}|)$ is relevant. However, restricting to a set of messengers that preserves the perturbativity (but not necessarily the equivalence) of the gauge couplings up to the purported unification scale $\sim 10^{16}$ GeV implies that F/M cannot be an integer multiple of $m_{3/2}$ (other than unity). Possible fractional values (such as $\frac{1}{2}m_{3/2}$ or $\frac{3}{2}m_{3/2}$) could only occur with messengers in non-vectorlike multiplets, that can be justifiably ignored due to the difficulty of

[3]If a higher rank group associated with the messengers broke to $\mathrm{SU}(3)_c$, it is possible that the effective n_3 could be negative due to gauge messengers [13]. However, this also causes the (mass)^2 for at least the first and second generation squarks to be negative, and therefore does not appear to be viable.

giving such fields a large supersymmetric mass. Under these constraints, Eq. (4) can be expanded

$$\begin{aligned} \tfrac{1}{5}\left(n_Q + 8n_u + 2n_d + 3n_L + 6n_e\right) &= \tfrac{33}{5} \\ 3n_Q + n_L &= 1 \\ 2n_Q + n_u + n_d &= 3\,, \end{aligned} \tag{5}$$

where n_X corresponds to the number of $X + \overline{X}$ pairs of vectorlike messenger multiplets in the SM representations (Q, u, d, L, e). The set of solutions are characterized by

$$\begin{aligned} n_Q &= 0 \qquad\qquad n_L = 1 \\ n_u + n_d &= 3 \\ n_u + n_e &= 4\,, \end{aligned}$$

meaning $n(Q, u, d, L, e)$ can only be one of (0, 0, 3, 1, 4), (0, 1, 2, 1, 3), (0, 2, 1, 1, 2), or (0, 3, 0, 1, 1). These sets of multiplets are degenerate at leading order, but give slightly differing results at next-to-leading order (e.g. two-loop expressions for gaugino masses, and two-loop contributions to the gauge β-functions above the messenger scale).

2.2 Multi-singlet models

Another approach to constructing a gauge-mediation model is to expand the messenger sector such that there are several singlets with either different supersymmetric masses, or different F-terms, or both. This approach has the advantage that matter in complete SU(5) representations is sufficient, thus naively preserving one-loop gauge-coupling unification. However, the supersymmetric mass scales or the F-terms (or both) must differ among the SU(3) $\times$ SU(2) $\times$ U(1) components fields, breaking the SU(5) ansatz.

There are two potential benefits of modifying the supersymmetric mass scale of SU(3) $\times$ SU(2) $\times$ U(1) component messenger fields. The first is a threshold effect, Eq. (3), whose size depends on F/M^2. A given gaugino mass could be increased (relative to $M \to$ large, with fixed F) by at most about 35%, if M is rather close to $\sqrt{F}$. In general it is hard to imagine how this could arise dynamically, although some ideas have been discussed in Ref. [9] (in an anomaly-mediated context). The second potential benefit of shifting the supersymmetric mass scale of messengers exploits the running gauge coupling. The gaugino mass induced at the messenger scale is proportional to the gauge coupling squared evaluated at the messenger scale $g^2(M)$, and so it is possible to shift a given gaugino mass by a factor $g^2(M_{\rm new})/g^2(M_{\rm old})$. This effect, however, is really a next-to-leading order correction. In practice, only g_3^2 evolves significantly (by at most about 40%) between the lowest and highest messenger scales (between about 10^5 to 10^9 GeV) that are consistent with gauge-mediation giving the dominant contribution to soft masses. One difficulty with both of these approaches is that several SM component fields of (say) complete SU(5) reps are charged under more than one gauge group of the SM, so that modifying the scale of a given pair of messengers affects several gaugino masses simultaneously.

We conclude that effects resulting from shifting the supersymmetric mass scale of messengers, by themselves, cannot reproduce any of the large ratios $B_1^{(1)}/|B_3^{(1)}| = 11/5$ or $|B_3^{(1)}|/B_2^{(1)} = 3$.

If several singlets communicate supersymmetry breaking from the dynamical supersymmetry breaking (DSB) sector to the messengers, it is not implausible that they could couple differently to SU(3) $\times$ SU(2) $\times$ U(1) component messenger fields. Then, given a small hierarchy of F-terms, is it trivial to construct a gauge-mediated model that has gaugino masses in a proportion indistinguishable from anomaly-mediation. For example, take the components of a $10 + \overline{10}$ coupled to two SM singlets X_1 and X_2 using the messenger superpotential

$$W \;=\; X_1 Q\overline{Q} + X_2 u\overline{u} + X_2 e\overline{e} \; . \tag{6}$$

With $F_{X_1}/3 = 7F_{X_2}/3 = m_{3/2}$, this model generates gaugino masses in exactly the same proportion as the one-loop β-function coefficients.[4]

2.3 Properties of the models

The two classes of models discussed above, namely the generalized messenger models and the multi-singlet model, generate the same result for the gaugino masses, but give somewhat different results for the scalar (mass)^2:

$$m_i^2 \;=\; 2\frac{F^2}{M^2}\sum_a C_a(i)\frac{g_a^4}{(16\pi^2)^2}n_a \qquad \text{(generalized messengers)} \tag{7}$$

$$m_i^2 \;=\; 2\frac{F^2}{M^2}\sum_a C_a(i)\frac{g_a^4}{(16\pi^2)^2}\left[m_a(X_1)\frac{F_{X_1}^2}{F^2} + m_a(X_2)\frac{F_{X_2}^2}{F^2}\right] . \qquad \text{(multi-singlet)} \tag{8}$$

The m factors are $m_a(X_1) = (1/5, 3, 2)$ and $m_a(X_2) = (14/5, 0, 1)$ respecting $m_a(X_1)+m_a(X_2) = (3, 3, 3)$, and we have taken the mass scale of the messengers M to be the same for both models. Notice that each gauge group is weighted by n_a in the generalized messenger models, whereas each gauge group is effectively weighted by n_a^2 in the multi-singlet model since each scalar (mass)^2 in the latter model is proportional to F^2. Thus, holding the gaugino mass spectrum fixed, these two classes of models give different predictions for the scalar masses. For example, squark masses tend to be about 15% lighter in the generalized messenger models. This illustrates that without specifying a particular messenger model, there is no unique prescription to translate a gaugino mass spectrum into a scalar mass spectrum.

Gauge coupling unification does not occur at 10^{16} GeV for the generalized messenger models; instead, g_1 is typically much larger than g_3, which is somewhat larger than g_2. Ordinarily the unification scale is defined by $g_1 \simeq g_2$, which in the generalized messenger models occurs at an intermediate scale $\sim 10^{10} \to 10^{12}$ GeV. Conversely, gauge coupling unification can occur in the multi-singlet model as long as the shifts in the β-functions due to the additional messenger fields are nearly independent of the gauge group (such as fields filling complete SU(5) reps).

[4]It is also possible that F-terms of different singlets could have opposite signs and be arranged such that the gaugino masses are in the same proportion as anomaly-mediation including the sign of M_3. However, we are not aware of any DSB or messenger model that could give this result.

A fascinating property of the generalized messenger models is that the predictions for the first and second generation squark masses are nearly identical to pure anomaly-mediation. This is evident from Eq. (7) at the messenger scale, where the dominant contribution proportional to g_3^4 is the same as anomaly-mediation. The prediction is also very well preserved under renormalization group (RG) evolution between the messenger scale and the weak scale, since the first and second generation scalar mass relations induced by gauge-mediation are very close to the renormalization group invariant mass relations of anomaly-mediation. This coincidence occurs precisely because n_3 is opposite in sign to $B_3^{(1)}$. Hence, this does not occur for slepton masses. Due to this interesting property, we concentrate most of the remaining discussion of gauge-mediated Wino NLSP models on the generalized messenger models.

The mostly Wino lightest neutralino is the NLSP and decays (dominantly) into a gravitino and a photon [14, 15, 16]. Depending on whether the fundamental supersymmetry breaking scale is smaller or larger than about a few hundred TeV, the Wino NLSP could decay either inside or outside a typical collider detector. If the decay NLSP $\rightarrow$ gravitino + photon were to occur well within a detector, it would be clearly evident with a hard photon emitted for every NLSP produced either directly or indirectly. This is a very robust signal in gauge-mediation [14] and completely different from anomaly-mediation. However, if the decay length is significantly longer than a typical collider detector,[5] the long-lived Wino NLSP is indistinguishable from a stable Wino LSP. We concentrate on this scenario for the remainder of the paper.

In supersymmetric models with a Wino (N)LSP, the mass splitting between the lightest chargino $\tilde{C}_1^{\pm}$ and the lightest neutralino $\tilde{N}_1$ is very small since both fields are nearly pure Wino-like states. Expressions for the mass splitting at tree-level [16, 7] and at one-loop [17, 16] have been calculated, with the intriguing possibility of a macroscopic $\tilde{C}_1 \rightarrow \tilde{N}_1 W^*$ decay length signal that has been studied in detail in Refs. [18, 19]. This is also an interesting signal of the gauge-mediated Wino NLSP models discussed here. However, it is not a useful distinction between gauge-mediation and anomaly-mediation because the decay lengths of the respective Wino (N)LSPs are comparable, as discussed below.

A complete set of parameters characterizing these models must also include $\tan\beta$ and μ. Demanding the proper electroweak symmetry breaking vacuum with the correct value of M_Z determines μ^2 as a function of the Higgs soft masses and $\tan\beta$ (at tree-level), leaving only the sign of μ unknown. Requiring that $m_{\tilde{\tau}_1}$ be greater than the current LEP bound (of about 90 GeV) implies that there is an upper bound on $\tan\beta$ as a function of the messenger parameters, shown in Fig. 1. Above about $F/M = 50$ TeV the limit disappears because the lightest stau mass is always larger than the LEP bound.

[5] The decay length scales as the fourth power of the fundamental supersymmetry breaking scale, and therefore could be anywhere from microns to the distance from the Earth to the Sun.

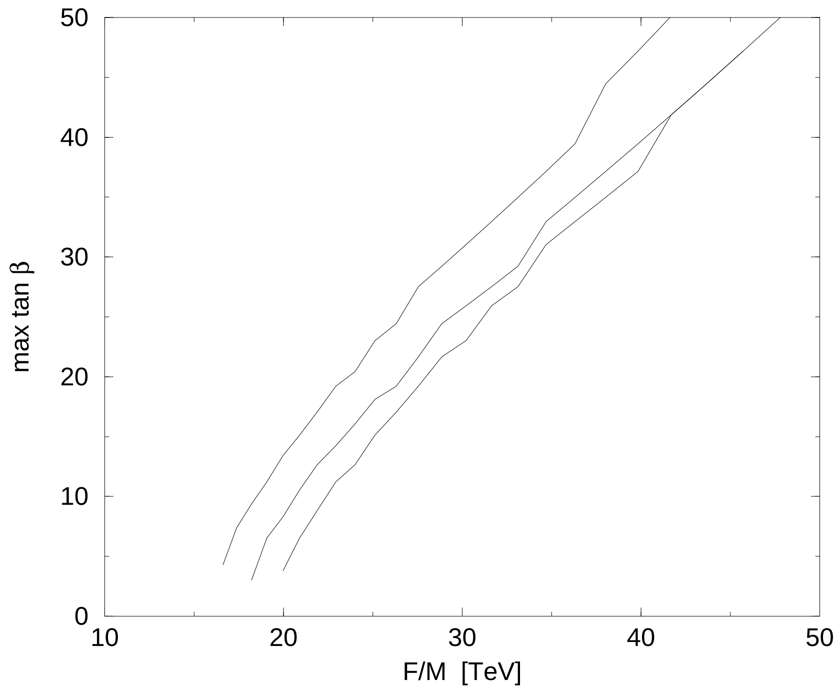

Figure 1: Maximum $\tan\beta$ as a function of F/M in generalized messenger models by requiring that $m_{\tilde{\tau}_1}$ is larger than the current LEP bound. The bottom, middle, and top lines correspond to $M = 10^5$, 10^7, and 10^9 TeV. The parameter space above and to the left of the lines is excluded.

3 Distinctions between anomaly-mediation and gauge-mediation

There are three central phenomenological differences between anomaly-mediation and gauge-mediation: the scalar spectrum is in general different, the sign of the gluino soft mass is different, and the Wino NLSP of gauge-mediation is unstable. However, none of these differences are necessarily trivial to establish in a collider experiment, as discussed below.

3.1 Scalar spectrum

Once the overall supersymmetry breaking scale F/M is established, the scalar spectrum of the gauge-mediated models is fixed, up to a logarithmic sensitivity to the messenger scale. Unlike anomaly-mediation, there is no reason to suggest there should be additional contributions to the matter scalars (not including the Higgs scalars) if gauge-mediation via SM interactions provides the dominant source of supersymmetry breaking. Indeed, the elegant resolution to the supersymmetric flavor problem via gauge-mediation would, in general, be lost with additional

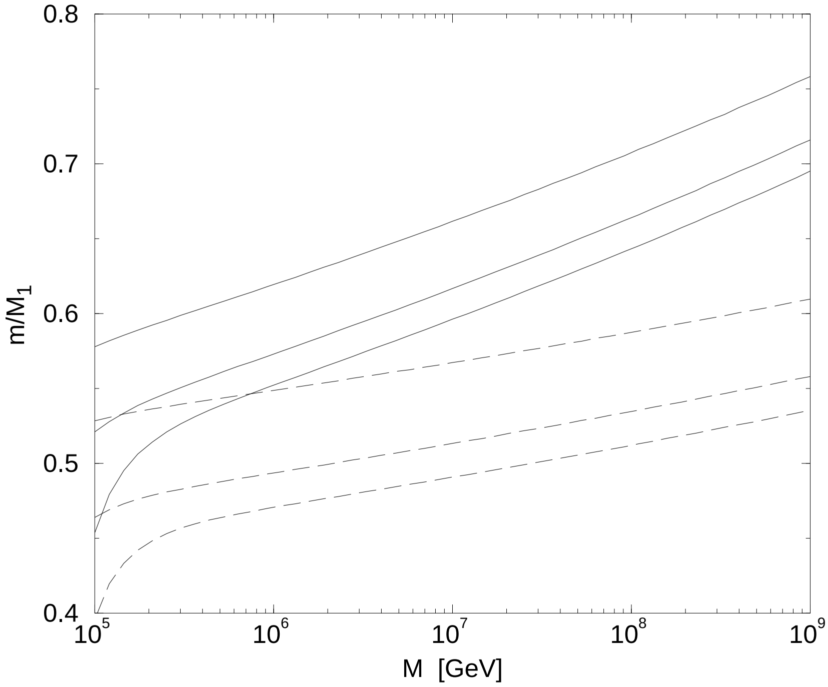

Figure 2: Contours of $m_{\tilde{e}_R}/M_1$ (solid lines) and $m_{\tilde{e}_L}/M_1$ (dashed lines) as a function of the messenger scale M. The top, middle, and bottom lines correspond to F/M = 20, 40, and 80 TeV, respectively.

contributions (unless they were flavor-independent, aligned, or very heavy[6]). Thus, the simplest way to exclude the gauge-mediated models discussed here is to experimentally verify that the scalar mass spectrum does *not* follow the gauge-mediated scalar spectrum. For example, the charged selectron masses fall in a relatively narrow mass range relative to M_1,[7] shown in Fig. 2. The size of the sleptons masses in anomaly-mediation, by contrast, are dependent on m_0, and therefore a priori completely unrelated to M_1.

In anomaly-mediation, it is not at all unreasonable that m_0 may be moderately small, meaning that it gives a significant contribution to sleptons to render them positive, but gives an insignificant contribution (or none at all) to squarks. This of course depends on the underlying origin of m_0, of which we remain agnostic. There is, in fact, a range of m_0 that implies the anomaly-mediated and gauge-mediated predictions for the left-handed first and second generation slepton masses are identical. The parameter space of this "worst nightmare" situation is shown in Fig. 3. Note that including experimental uncertainties would widen the overlapping range of

[6]See Ref. [20] for a well-motivated example of just such a possibility.

[7]The ratio to the Bino mass (instead of the lighter Wino mass) was chosen to minimize dependence on higher order corrections (see Sec. 4).

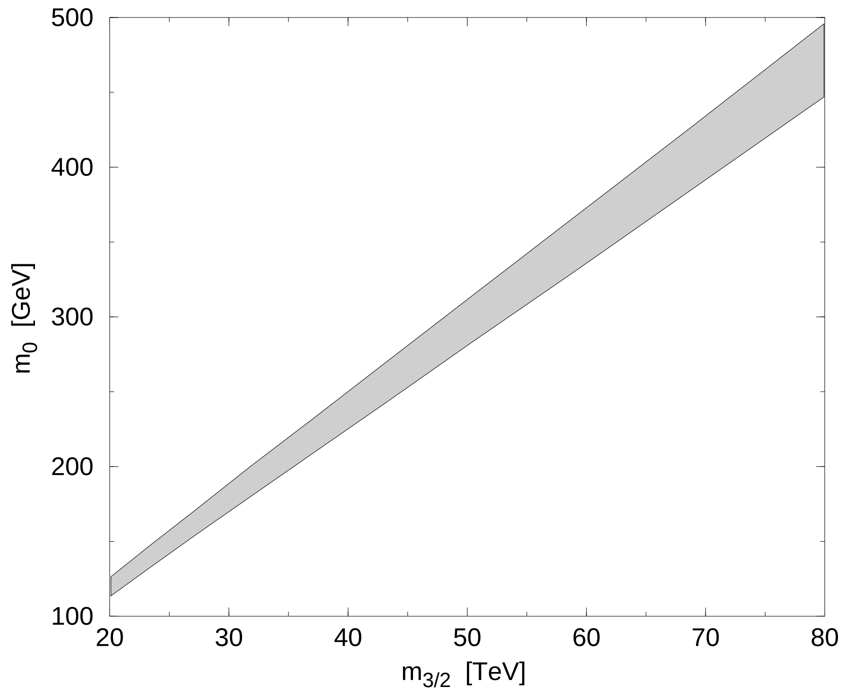

Figure 3: Range of m_0 as a function of $m_{3/2} = F/M$ that implies the anomaly-mediated and generalized gauge-mediated models predict the same left-handed first and second generation slepton masses. The shaded band is the result of varying the messenger scale M between 10^5 to 10^9 GeV in the gauge-mediated model.

$m_{3/2} = F/M$ for a given m_0.

It is therefore possible that the only differences in the scalar sector between an anomaly-mediated model with m_0 as shown in Fig. 3 and a generalized gauge-mediated model are ultimately related to: $m_{\tilde{\ell}_R}$, μ, and the scalar trilinear couplings. In the remainder of this section we discuss to what extent these observables provide useful distinguishing criteria between anomaly-mediation and gauge-mediation.

In the generalized gauge-mediated Wino NLSP models, the first and second generation right-handed slepton mass m_{ℓ_R} is always larger than the corresponding left-handed slepton mass m_{ℓ_L}, due to the large ratio $n_1/n_2 = 33/5$. Explicitly, there are three contributions to the slepton mass difference $m^2_{\ell_R} - m^2_{\ell_L}$: the gauge-mediated contribution at the messenger scale, the RG contribution, and the D-term contribution. The D-term contribution is accidentally rather small due to a numerical cancellation, and can be neglected. The other contributions are

$$\left[m^2_{\ell_R} - m^2_{\ell_L}\right]_{\rm mess} = \frac{3}{2}\frac{n_2}{(16\pi^2)^2}\left[\frac{3n_1}{5n_2}g_1^4 - g_2^4\right]\frac{F^2}{M^2} \tag{9}$$

$$\left[m^2_{\ell_R} - m^2_{\ell_L}\right]_{\rm RG} \simeq 6\frac{n_2^2}{(16\pi^2)^3}\left[\frac{3n_1^2}{5n_2^2}g_1^6 - g_2^6\right]\frac{F^2}{M^2}\ln\frac{M}{m_\ell} , \quad (10)$$

that in practice are numerically roughly comparable. The ratio can be approximately written as

$$\frac{m^2_{\ell_R} - m^2_{\ell_L}}{m^2_{\ell_L}} \simeq (0.25 \pm 0.05) + 0.04 \ln\frac{M}{10^5\ \text{GeV}} , \quad (11)$$

where the ± 0.05 arises from the variation of F/M throughout the range $20 \to 80$ TeV. This is very different from anomaly-mediation, where the difference between the left-handed and right-handed slepton masses is less than a few percent throughout most of the parameter space [7].

The bilinear supersymmetric Higgs mass, μ, feeds into several low energy observables, including the heavier chargino, the two heaviest neutralinos (assuming μ is larger than M_1), the heavier Higgs scalar masses, and the off-diagonal left-right (LR) squark and slepton mixing. Hence, determining the value of μ from experiment can be done via several different classes of signals.

In both the anomaly-mediated and gauge-mediated models discussed here, it is generally a good approximation throughout the parameter space that $\mu^2 \sim -m^2_{H_u}$. In anomaly-mediation, there is an interesting (apparently accidental) cancellation between the renormalization group contributions that feed into $m^2_{H_u}$ due to the presence of a nonzero m_0 (that breaks the renormalization group invariance of the anomaly-mediated spectrum). The result is a "focusing" effect [10, 21] that renders $m^2_{H_u}$ quite insensitive to large changes in m_0. In particular, $m^2_{H_u}$ is determined essentially by just the anomaly-mediated value that is approximately

$$m^2_{H_u} \simeq Y_t^2\left(-16g_3^2 - 9g_2^2 + 18Y_t^2\right)\left(\frac{m_{3/2}}{16\pi^2}\right)^2 , \quad (12)$$

or that roughly $(-m^2_{H_u})^{1/2}$ is about $2.5\, m_{3/2}/(16\pi^2)$. Therefore, in an anomaly-mediated model with a universal additional scalar mass m_0, the value of μ is fixed once the scale of the gaugino masses has been established.

In gauge-mediation the Higgs scalar masses are also determined once the messenger sector is fixed and the scale of the gaugino masses has been established. However, no dynamical origin for μ was given, and indeed it is possible that the Higgs soft masses could be affected by the mechanism that ultimately determines μ (see e.g. [22]). For this reason, observables that depend on μ are not particularly reliable distinctions between anomaly-mediation and gauge-mediation, unless the gauge-mediated contributions to the Higgs soft masses dominate over all other possible contributions.

Another interesting observable is the decay length of $\tilde{C}_1 \to \tilde{N}_1 W^*$. This is also, unfortunately, not a useful distinction between anomaly-mediation and gauge-mediation for two reasons. First, the one-loop corrections dominate throughout the parameter space of interest, and to a very good accuracy depend only on kinematical functions of M_2 and M_W [16]. This contribution is therefore the same for a given Wino mass. Second, the smaller tree-level corrections [16, 7] depend sensitively on μ (and $\tan\beta$), that we have argued is not a reliable distinction. Thus, while the macroscopic decay length of the lightest chargino is an excellent signal of a Wino (N)LSP, it does not provide any useful information to distinguish the mediation of supersymmetry breaking.

Finally, at leading order scalar trilinear couplings, A_f, are generated in anomaly-mediation, but not in gauge-mediation. They do reappear in gauge-mediation after renormalization group evolution to the weak scale, but are usually smaller (in absolute value) than and opposite in sign to the anomaly-mediated values. These couplings affect the (mass)^2 matrix for the sfermions, but to a good approximation for moderate to large $\tan\beta$, they only significantly impact the stop mass matrix. This is because the off-diagonal term for up-type sfermions is $m_f(A_f - \mu/\tan\beta)$ whereas for down-type sfermions it is $m_f(A_f - \mu\tan\beta)$, which shows that the term proportional to μ is significantly diminished (enhanced) relative to A_f for up-type (down-type) sfermions. Thus, the splitting between the heavier stop ($\tilde{t}_2$) and the lighter stop ($\tilde{t}_1$) mass eigenstates is generally larger in anomaly-mediation. Taking a ratio, such as $(m^2_{\tilde{t}_2} - m^2_{\tilde{t}_1})/m^2_{\tilde{t}_2}$, also eliminates the dependence on m_0 in anomaly-mediation, and therefore provides a useful additional distinction. Note, however, that the gauge-mediation prediction of nearly zero scalar trilinear couplings at the messenger scale relies on the assumption that the couplings between messenger fields and MSSM matter fields are very small [13].

3.2 Sign of gluino soft mass

In general, the soft mass of the gluino in the MSSM may be complex. After a field redefinition of the gluino, the phase of the gluino soft mass appears only in the interaction of a gluino and a chiral multiplet (see the Appendix for details). Furthermore, the phase cancels in processes that involve a vertex with a chiral multiplet *and* its hermitian conjugate. The phase reappears only in a chirality violating interaction (such as an interaction with a Higgs) or a "fermion number violating" interaction. One-loop examples of such interactions are shown in Fig. 4.

A significant CP-violating phase in the gluino soft mass, i.e. $\arg(M_3)$ not close to 0 or π, gives large contributions to CP-violating processes, particularly the electric dipole moment of the neutron [23, 24]. Here we are interested in the processes of Fig. 4 that can distinguish a CP-even gluino soft mass ($\arg(M_3) = 0$) from a CP-odd gluino soft mass ($\arg(M_3) = \pi$), through necessarily CP conserving processes.

Evidently several processes are affected by the gluino soft mass sign. These include fermion masses, fermion-fermion-Higgs interactions, scalar trilinear couplings, squark LR mixing, quark-squark-gaugino interactions, etc. One-loop corrections to the pole masses of quarks and squark LR mixing (mass)^2 have been calculated in e.g. Ref. [17]. The one-loop correction to the b mass is particularly interesting, since the left-right squark mixing is proportional to $\mu\tan\beta$ for moderate to large $\tan\beta$, and thus can give an $\mathcal{O}(1)$ correction [25]. This suggests that accurately measuring the Higgs-b-$\bar{b}$ coupling would be sensitive to the gluino soft mass sign. Having a large sample of Higgs events with excellent b tagging would be essential. However, this process becomes increasingly difficult for decreasing $\tan\beta$, and also requires an independent measurement of the

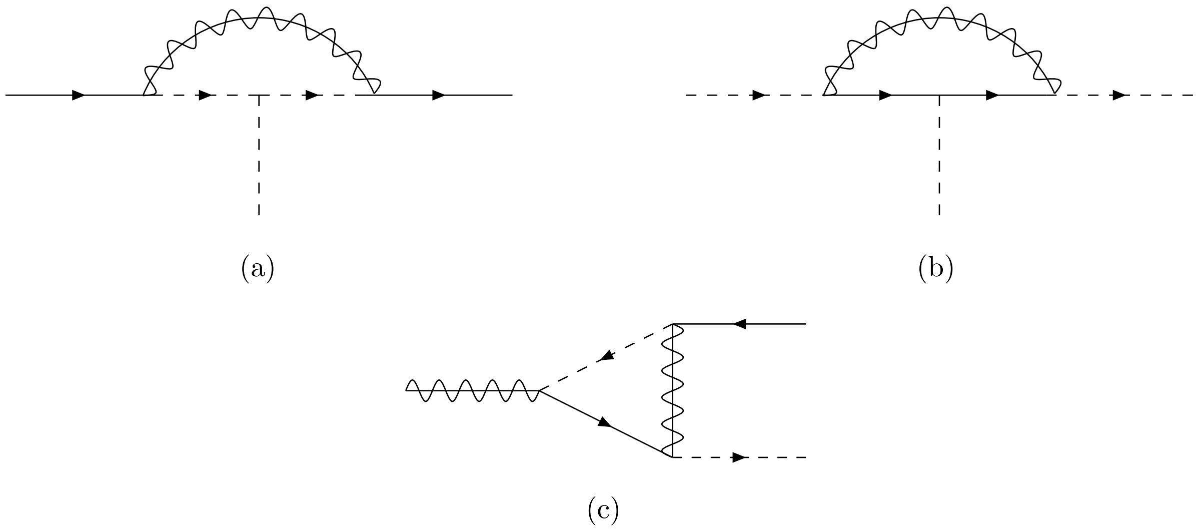

Figure 4: One-loop diagrams that are proportional to the phase $\arg(M_3)$ of the gluino soft mass: (a) a one-loop correction to a fermion-fermion-Higgs interaction, (b) a one-loop correction to a scalar trilinear coupling, and (c) a one-loop correction to the gaugino-quark-squark coupling. The arrows denote the flow of baryon number.

sign of μ.

Another class of processes, shown in Fig. 4(c), are the one-loop gluino corrections to the quark-squark-gaugino vertex. These corrections arise in gaugino decay $\tilde{G} \to q\tilde{q}^{(\prime)}$ and/or squark decay $\tilde{q} \to \tilde{G}q^{(\prime)}$, depending on the kinematics. Here $\tilde{G}$ can be any gaugino, and the prime denotes the SU(2) doublet partner field (for decays involving a chargino). These radiative corrections have the advantage that they are proportional to g_3^2, but the disadvantage that they are suppressed by $|M_3|^2$ and must involve squarks that are typically much heavier than sleptons.

Several other processes involving the diagrams of Fig. 4 might be useful. Determining the best experimental observable depends on the precision to which particular sparticle properties are measured and the collider that is used.

3.3 NLSP decay

One apparently obvious distinction between anomaly-mediation and gauge-mediation is that the Wino NLSP of a gauge-mediated model decays into a gravitino plus a photon. Even if the decay length is significantly larger than the scale of a collider detector, a statistically significant excess of sparticle production events with one (or two) hard photon(s) could experimentally establish that the Wino is unstable (otherwise, place a lower bound on its decay length). To confirm that the Wino is unstable, in principle only a few events would be necessary, as long as SM backgrounds can be reduced to a negligible level. The probability that one NLSP decays within the distance L ($\ll L_{\rm NLSP}$) of order the detector size, where $L_{\rm NLSP} = c/\Gamma_{\rm NLSP}$, is $1 - e^{-L/L_{\rm NLSP}} \sim L/L_{\rm NLSP}$.

Thus, one would expect about one NLSP decay for every $L_{\rm NLSP}/L$ NLSPs produced. However, as discussed above, the decay length could be enormous compared with the scale of a detector, and thus be well beyond the range of ordinary collider experiments. In this case, the gauge-mediated Wino-related collider signals are indistinguishable from anomaly-mediation (or any other supersymmetric model that predicts a stable Wino). The difference might be detectable with a very long baseline experiment to measure NLSP decay, or, if there is a cosmologically significant relic density of Wino LSPs of anomaly-mediation [7, 26], using dark matter detection experiments.

4 Higher order corrections

The equivalence of the gauge-mediated and anomaly-mediated gaugino masses holds to leading order (LO), but not to higher orders. This is simply a consequence of the different origin of the soft masses. Higher order corrections are generally expected to be suppressed by a one-loop factor $1/16\pi^2$ times order one couplings and coefficients, relative to the leading order corrections. There are, however, important next-to-leading (NLO) two-loop corrections to the gaugino masses [27] that are much larger than might be naively expected [28]. The most important correction relevant to this discussion is the two-loop contribution to M_2 due to the $g_2^2 g_3^2 M_3$ term. In anomaly-mediation, this takes the form

$$M_2^{\rm AM}|_{\rm NLO} \;=\; M_2^{\rm AM}|_{\rm LO}\left[1+\frac{B_{23}^{(2)}g_3^2}{B_2^{(1)}16\pi^2}\right] \tag{13}$$

where $B_{23}^{(2)}=24$ is the rather large two-loop coefficient. The NLO result is about 20% larger than the LO result at the weak scale [7]. In gauge-mediation, there is also a correction from the renormalization group evolution that explicitly depends on the logarithm of the ratio of scales. Specifically, this correction can be approximated as

$$M_2^{\rm GM}|_{\rm NLO} \;=\; M_2^{\rm GM}|_{\rm LO}\left[1-\frac{n_3 B_{23}^{(2)}g_3^4}{n_2(16\pi^2)^2}\ln\frac{M}{M_2}\right]\,. \tag{14}$$

The gauge-mediated NLO expression for M_2 is typically a few percent *smaller* than the LO result, depending on the messenger scale M.

The other gaugino masses M_1 and M_3 receive at most a few percent correction to their LO values from the NLO pieces of the β-function, in both AM and GM models. Since one-loop threshold corrections are of the same order (if not significantly larger, especially for M_3), the NLO β-function corrections for these masses can be neglected.

4.1 Modifications to account for M_2

The large correction to M_2 in the anomaly-mediated approach naively suggests that accurately measuring the ratio M_1/M_2 would distinguish anomaly-mediation from gauge-mediation at next-to-leading order. However, it is not hard to imagine that messengers could generate the approximate proportion $(n_1 : n_2 : n_3) \sim (33/5 : 1.2 : 3)$. Perhaps the simplest possibility is to assume that F/M^2 for the $L + \overline{L}$ multiplet is about 0.9, while all of the other multiplets have $F/M^2 \ll 1$. This generates a rather large positive one-loop threshold correction of about the right size for M_2 only.[8] The multi-singlet model with differing F-terms could also reproduce this ratio, but requires three different singlets coupling to the three SM components of the $10 + \overline{10}$, with F-terms in the proportion $(F_{X_Q} : F_{X_u} : F_{X_e}) = (4, 22, 25)$. Thus, the gauge-mediated Wino NLSP models could approximately reproduce the NLO gaugino mass predictions of anomaly-mediation, although one must make some slight modification to the messenger sector that is admittedly rather ad hoc.

5 Conclusions

There exist gauge-mediated Wino NLSP models that predict the gaugino masses, the first and second generation squark masses, and potentially the left-handed first and second generation slepton masses are nearly equivalent to the predictions of an anomaly-mediated model with a small universal additional scalar mass. The sbottom masses, stau masses, heavier Higgs masses, and heavier chargino and neutralino masses are in general somewhat different due to a differing value of μ (determined from EWSB constraints). But, we have argued that these observables are not useful distinctions between the two classes of models because the mechanism for the dynamical generation of μ in gauge-mediation, which could affect the Higgs soft masses, is unknown. This leaves only the ratios $(m^2_{\tilde{\ell}_R} - m^2_{\tilde{\ell}_L})/m^2_{\tilde{\ell}_L}$ and $(m^2_{\tilde{t}_2} - m^2_{\tilde{t}_1})/m^2_{\tilde{t}_2}$ as useful parameter-independent experimental criteria to distinguish between anomaly-mediation and the gauge-mediated models discussed here.

The differing sign of the gluino soft mass is perhaps the clearest distinction between anomaly-mediation and gauge-mediation. Several one-loop processes are sensitive to this sign. Probably the most promising way to measure the sign of the gluino soft mass is to accurately measure the one-loop gluino-induced correction to the Higgs-b-$\bar{b}$ coupling. This would no doubt require observing plenty of Higgs events with excellent b tagging.

The NLSP of any gauge-mediated model is unstable. Observing the decay of NLSP $\to$ gravitino plus a photon would strongly suggest gauge-mediation, although the decay length could be well beyond the sensitivity of any collider experiment. In this scenario, a long-lived Wino NLSP of gauge-mediation is indistinguishable from a stable Wino LSP of anomaly-mediation in ordinary collider experiments. Establishing the (in)stability of the Wino would thus require either a very long baseline experiment to search for its decay, or a dark matter detection experiment to search for a cosmologically significant relic density of Wino LSPs.

[8]In this case, higher order corrections from messenger contributions could also be important [29].

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Appendix: The Lagrangian for a complex gluino soft mass

Assume the gluino soft mass is complex $M_3 = |M_3|e^{i\theta}$ and that the phase is physical (i.e., cannot be rotated into some other soft breaking quantity). The relevant pieces of the softly broken interaction Lagrangian involving the gluino are

$$\mathcal{L}_{\tilde{g}} = \mathcal{L}_{\tilde{g},\mathrm{gauge}} + \mathcal{L}_{\tilde{g},\mathrm{chiral}}$$

where

$$\begin{aligned} \mathcal{L}_{\tilde{g},\mathrm{gauge}} &= -i\lambda^{\dagger a}\overline{\sigma}^{\mu}\mathcal{D}^{a}_{\mu}\lambda^{a} - \tfrac{1}{2}(M_3\lambda^a\lambda^a + h.c.) \\ \mathcal{L}_{\tilde{g},\mathrm{chiral}} &= \sqrt{2}g_3\sum_i\left(i\phi_i^* T_i^a\psi_i\lambda^a + h.c.\right) \ . \end{aligned}$$

λ^a is the 2-component gluino spinor with $a = 1\ldots 8$, the $\sum_i$ is over all chiral multiplets, T_i^a is the SU(3) matrix for the i^{th} representation, ϕ and ψ are the complex scalar and 2-component spinor for the chiral multiplet, and the covariant derivative acting on the gluino is

$$\mathcal{D}^a_\mu\lambda^a = \partial_\mu\lambda^a - g_3 f^{abc}A^b_\mu\lambda^c \ .$$

Under the field rotation $\lambda^a \to \lambda^a e^{-i\theta/2}$, $\mathcal{L}_{\tilde{g},\mathrm{gauge}}$ is invariant (except, of course, that $M_3 \to |M_3|$), while $\mathcal{L}_{\tilde{g},\mathrm{chiral}}$ becomes

$$\sqrt{2}g_3\sum_i\left(i\phi_i^* T_i^a\psi_i\lambda^a e^{-i\theta/2} + h.c.\right) \ .$$

In four component notation, the quark–squark–gluino interaction Lagrangian (see Eq. (C89) in Ref. [30]) in the MSSM becomes

$$-\sqrt{2}g_3 T^a_{jk}\sum_i\left(\tilde{q}^{j*}_{iL}\overline{\tilde{g}}_a P_L q^k_i e^{-i\theta/2} - \tilde{q}^{j*}_{iR}\overline{\tilde{g}}_a P_R q^k_i e^{i\theta/2} + h.c.\right) \qquad (15)$$

where the sum is over all quarks $i = u, d, c, s, t, b$. This agrees with the result found in Ref. [24].

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